Soft Computing Approach to Crack Detection and FPGA Implementation

Arati M. Dixit[1], Harpreet Singh[1], Thomas Meitzler[2]

[1]Department of Electrical and Computer Engineering, Wayne State University, Detroit, MI, 48202

[2]US Army RDECOM-TARDEC, Survivability Research, Warren, MI, 48397-5000

ABSTRACT

Considerable interest has existed in the literature for a long time in support of real-time crack detection Non-Destructive Techniques (NDT) in a variety of applications. Various authors [1, 15, 16, and 17] have suggested different approaches in finding a solution to this problem. In this paper we suggest a Soft Computing approach using Fuzzy Logic as an effective method to take up this problem. It is also desirable to develop chip which can be used for detection of crack. The objective of this paper is to report on efforts to develop an automated procedure to detect the crack and to devise technique so that the proposed method can be easily implemented on a chip. The Fuzzy Inference System developed is supported by the rule base. A Very Large Scale Integration (VLSI) circuit for the detection of crack is developed on the basis of the Fuzzy Logic Model using a Hardware Description Language (HDL). Field-Programmable Gate Array (FPGA) implementation and testing of this circuit is done.

Keywords: Fuzzy Logic, Non-Destructive Techniques, Crack Detection, NeuroFuzzy Logic, Mamdani and Sugeno methods, FPGA

I. INTRODUCTION

Crack Detection in materials is a well-known problem found in various commercial, military, medical, automobile applications like bridges, turbines, armor plates, bones, teeth etc. There has been a long standing interest in developing non destructive techniques for determining the presence of cracks in materials. This problem is quite important to issues related to the security and safety of Soldiers as it affects armored vehicles and Soldier's body armor plates on the battlefield. The American Society of Non Destructive Testing (ASNT) [13] defines Non Destructive Testing as '*the testing of a specimen that determines its serviceability without damage that could prevent its intended use*'. The NDT for crack detection endeavors to improve the reliability, quality level of product material and operational readiness of armored vehicles and Soldier's body armor at the battlefield. The authors present a new Fuzzy Logic based method supported by Field-Programmable Gate Array FPGA implementation for crack detection in armor plates. Our approach uses the theory of fuzzy logic and develops a fuzzy model to determine the degree of crack in armor plates. Furthermore this crack detection fuzzy model's circuit design is implemented with FPGA [7], with an intention of embedding that model on a chip, which can fit in a crack detection handheld device.

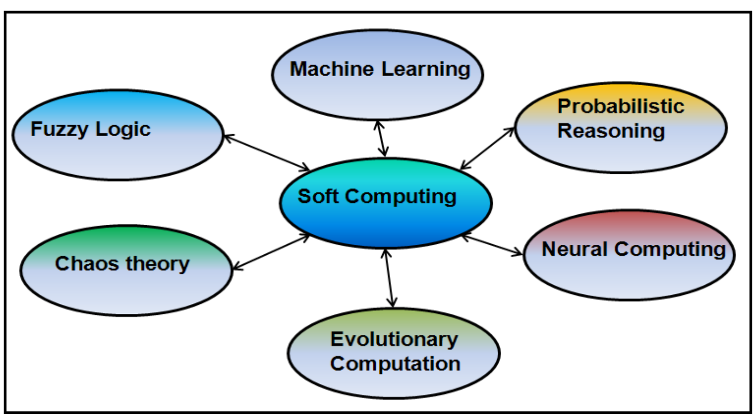


Fig. 1 Components of Soft Computing

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
21 OCT 2010	**Journal Article**	**06-02-2010 to 18-08-2010**

4. TITLE AND SUBTITLE
Soft Computing Approach to Crack Detection and FPGA Implementation

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Arati Dixit; Harpreet Singh; Thomas Meitzler

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Wayne State University,Department of Electrical and Computer Engineering,5401 Cass Ave., ,Detroit,Mi,48202

8. PERFORMING ORGANIZATION REPORT NUMBER
; #21283

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army TARDEC, 6501 East Eleven Mile Rd, Warren, Mi, 48397-5000

10. SPONSOR/MONITOR'S ACRONYM(S)
TARDEC

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
#21283

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Considerable interest has existed in the literature for a long time in support of real-time crack detection Non-Destructive Techniques (NDT) in a variety of applications. Various authors [1, 15, 16, and 17] have suggested different approaches in finding a solution to this problem. In this paper we suggest a Soft Computing approach using Fuzzy Logic as an effective method to take up this problem. It is also desirable to develop chip which can be used for detection of crack. The objective of this paper is to report on efforts to develop an automated procedure to detect the crack and to devise technique so that the proposed method can be easily implemented on a chip. The Fuzzy Inference System developed is supported by the rule base. A Very Large Scale Integration (VLSI) circuit for the detection of crack is developed on the basis of the Fuzzy Logic Model using a Hardware Description Language (HDL). Field-Programmable Gate Array (FPGA) implementation and testing of this circuit is done.

15. SUBJECT TERMS
Fuzzy Logic, Non-Destructive Techniques, Crack Detection, NeuroFuzzy Logic, Mamdani and Sugeno methods, FPGA

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Public Release**	**13**	

Soft computing provides an effective tool to deal with complex problems in which there is lack of precision, certainty, and complete truth. The concept of soft computing introduced by Prof. Zadeh in [14] as "*Soft Computing is tolerant of imprecision, uncertainty, partial truth, and approximation than the traditional Hard Computing. The role model for Soft Computing is the human brain*". Soft Computing has now evolved to constitute following components: Fuzzy Logic, Neural Computing, Evolutionary Computation, Machine Learning, Probabilistic Reasoning, and Chaos theory [14]. The beauty of these components is that they combine together in different combinations to emerge as a strong technology to tackle complicated problems. Note that the Fuzzy Logic is the heart of the soft computing. Fuzzy Logic approximates the modeling of unknown system or object. Neural Computing models the systems with help of neural networks. Evolutionary Computation deals with optimization. Machine Learning component focuses on algorithm design and development where data can be changed or controlled by machine. Probabilistic reasoning takes into consideration and analyzes the result of system influenced by the probabilistic uncertainty. Chaos theory studies the behavior of dynamic systems susceptible to initial conditions. Fuzzy Logic [5] uses the Fuzzy set theory. It supports smooth, continuous variation of statement values between values '0' and '1' rather than just sticking to 0(low) and 1(high) as found in digital logic. The essence of Fuzzy Logic is that it behaves like a human mind.

This paper is organized in the following manner. Section II presents the crack detection test system description and methodology and also provides some literature review. Section III discusses the fundamental theory of fuzzy systems, fuzzy models and fuzzy logic-based modeling techniques. The proposed Crack Detection Fuzzy Inference System is given in Section IV. Section V presents an FPGA Implementation of crack detection system. Finally Section VI concludes the paper.

II. CRACK DETECTION: Test System Description and Methodology

The fuzzy logic approach [3] can be efficiently used to model any crack detection system. The nature of application where it is used would decide what kind of knowledge base is required to develop the Fuzzy Inference System. The fuzzy logic approach will involve an element of Artificial Intelligence in any crack detection system.

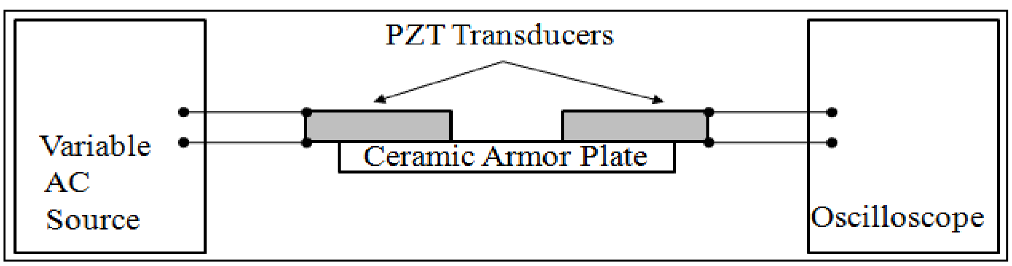


Fig. 2 Crack Detection Test System Circuit with a ceramic plate

A previous paper by Meitzler et. al [1] describes a method for the ultrasonic crack detection in ceramic Vehicle Body Armor Support System (VBASS) plates. In this reference the approach used is as shown in Fig. 2.The technique used is briefly summarized as a ready reference to aid the reader. Meitzler used two piezoelectric lead zirconate titanate (PZT) transducers. One of these transducers is connected to the variable AC source and the other is connected to the oscilloscope for transmitted energy and excited vibrational mode analysis. PZT transducers are used to excite and measure the resonances mode of rectangular, ceramic armor plates in 50- 300 kHz range of frequencies. The authors in reference [1] use the test circuit as seen in Fig. 2 to determine the existence of cracks or change in the mechanical structure of the material by comparing the output voltage waveforms with that of an undamaged plate using metrics. An attempt is made to propose an automated procedure to detect cracks or plate damage. These vibration waveforms are also used to extract important information in terms of input driving frequency, output average Root Mean Square (RMS) and standard deviation. The analysis of these waveforms leads to interesting results which help to distinguish between the plates of differing status. These observations lead to conclusion about mapping the status of the plate Є {damaged, undamaged, and slightly damaged} with extracted factors like input driving frequency, output average RMS voltage and standard voltage deviation. This generates a sufficiently large database with parameters {status of plate, Frequency, average RMS, Standard Deviation}. This database becomes instrumental in defining the relationship between Input Parameters= {Frequency, average RMS,

Standard Deviation} and output parameter= {*Status of Plate*}. A new term is coined to define the severity of crack as 'Degree of Crack'. The degree of crack essentially portrays the nature of the plate. The 'Degree of Crack=0' indicates plate is undamaged and 'Degree of Crack=1' indicates that the plate is damaged. As the severity of crack increases, the value of *Degree of Crack* increases. The Crack Detection Test System Circuit as shown in Fig. 2 is used for the development of an automated Fuzzy Model. Thus the Fuzzy model is multiple input single output system. The multiple inputs are: Input frequency, Output Average Root Mean Square voltage and Standard voltage Deviation. The output is the Degree of Crack.

III. FUZZY SYSTEMS

A fuzzy system is a system that is based on the Fuzzy Logic. A Fuzzy system model for Crack Detection as seen in Fig. 3 consists of following main components:

1) Numerical Data Inputs: The vibration waveforms are used to extract some significant information that can help to determine the Degree of Crack. The numerical values for Input Frequency, Output Average Root Mean Square (RMS) and Standard Deviation voltage are used as input for the Fuzzy Model.
2) Numerical and Linguistic Data Outputs: The Degree of Crack is the output for the proposed model such that,

$$0 \leq \text{ Degree of Crack} \geq 1$$

   The Linguistic output Є {Undamaged, slightly damaged, Damaged, Unknown}.
3) Fuzzification: It maps an observed non-fuzzy input space into suitable linguistic values, which can be viewed as labels of fuzzy sets.
4) Fuzzy Inference Engine: It consists of:
   - A rule base: Fuzzy rule can be expressed as: *If input is A, then output is B*, where A and B are the input and output linguistic values defined. These rules are formulated on the basis of past experience, knowledge about the system that is to be developed. Here *A* is called as an antecedent and *B* is called as a consequent.
   - Fuzzy rule database: Defines the membership functions for each input and output, which are used by the fuzzy rules and forms.
   - Reasoning mechanism: Obtains the output by performing the inference procedure on the given conditions and the formed rules. The result is obtained by aggregating the result of each rule in the fuzzy rule base.
5) Defuzzification: This component takes inputs as aggregated fuzzy dataset and maps it to a nonfuzzy output value 'Degree of Crack'.

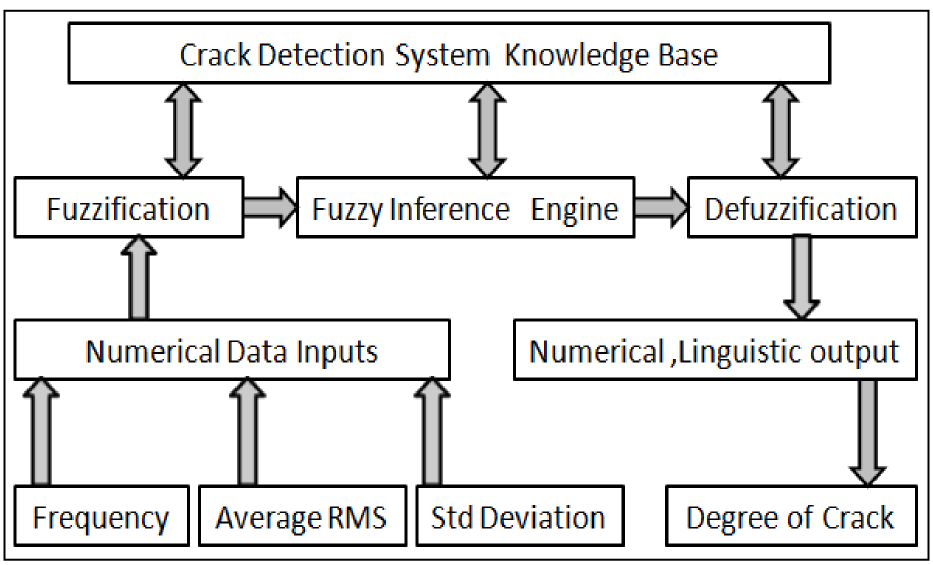


Fig. 3 Fuzzy system model for Crack Detection

IV. CRACK DETECTION FUZZY INFERENCE SYSTEM

Fuzzy logic can play a significant role in an application such as crack detection systems [2, 4, and 6]. Fuzzy logic supports the use of a set of rules which portrays the relationship between the input and the output variables. These user-defined set of rules governing the crack detection system are updated until the desired result from the system is not obtained. The Fuzzy model is multiple input single output system. The multiple inputs include: Input frequency, Output Average Root Mean Square (RMS) voltage and Standard voltage Deviation. The output is *Degree of Crack* or N*ature of Plate*. The multiple input single output Crack Detection Fuzzy Inference System is shown in Fig. 4.

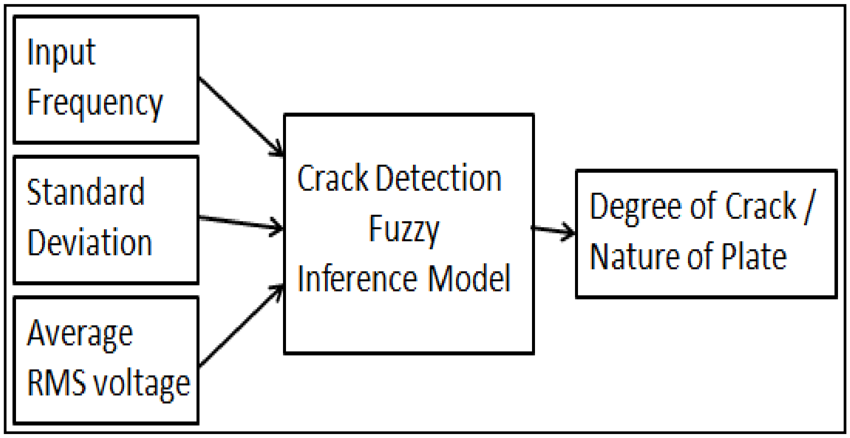


Fig. 4 Multiple input single output Crack Detection Fuzzy Inference System

The reference [1] has presented some results for the crack detection for the test circuit as seen in Fig. 2. On the basis of these results an attempt is made to assign the labels to different ranges of Input frequency, Output Average Root Mean Square voltage and Standard voltage Deviation. These linguistic labels are eventually assigned some degree of membership as seen in equation 1. The Table 1 shows linguistic labels for the different factors.

Table 1: Labels for the Input function for Crack Detection Fuzzy Inference System

Labels	**Range**	**Low**	**Medium**	**High**
Frequency (KHz)	1-124	1 – 60	61 - 90	91 - 124
Average Root Mean Square voltage	0-0.002971	≤ 0.00199	>0.00199 & <0.002971	≥ 0.002971
Standard Deviation	0- 0.0001889	≤ 0.00003229	>0.00003229 &<0.0001889	≥0.0001889

The function for factor Frequency with linguistic label is defined in equation (1). These labels Low, Mild and High are assigned a degree of triangular membership function as seen in equations (2) to (4) for frequency in equation (1). Similarly other factors like Average Root Mean Square Voltage and Standard Deviation can be defined as seen in Table 1.

$$\text{Frequency}(x) = \begin{cases} \text{Low} & \text{if} \quad 1 \le x \le 60 \\ \text{Medium} & \text{if} \quad 61 \le x \le 90 \\ \text{High} & \text{if} \quad 91 \le x \le 124 \end{cases} \tag{1}$$

$$\text{Low}\,(x) = \begin{cases} 0, x \le 1, \\ (0.4 - x)/0.3, x \in (0,0.4) \\ 0, x \ge 0.4 \end{cases} \tag{2}$$

$$\text{Medium}\,(x) = \begin{cases} 0, x \le 0.1 \\ (x-0.1)/(0.4), x \in (0.1, 0.5) \\ (0.9-x)/(0.4), x \in (0.5, 0.9) \\ 0, x \ge 0.9 \end{cases} \tag{3}$$

$$\text{High}\;\;(x) = \begin{cases} 0, x \le 0.6 \\ (x-0.6)/(0.4), x \in (0.6, 1) \\ 0, x \ge 1 \end{cases} \tag{4}$$

$$\text{DegreeOfCrack}(x) = \begin{cases} \text{Low} & \text{if} \quad \text{trimf(x,[-0.4, 0, 0.4])} \\ \text{Medium} & \text{if} \quad \text{trimf(x,[1, 0.5, 0.9])} \\ \text{High} & \text{if} \quad \text{trimf(x,[0.6, 1, 1.4])} \end{cases} \tag{5}$$

where trimf(x, [a, b, c]) is the triangular function [11] with a, b and c are left feet, right feet and the peak of the triangle.

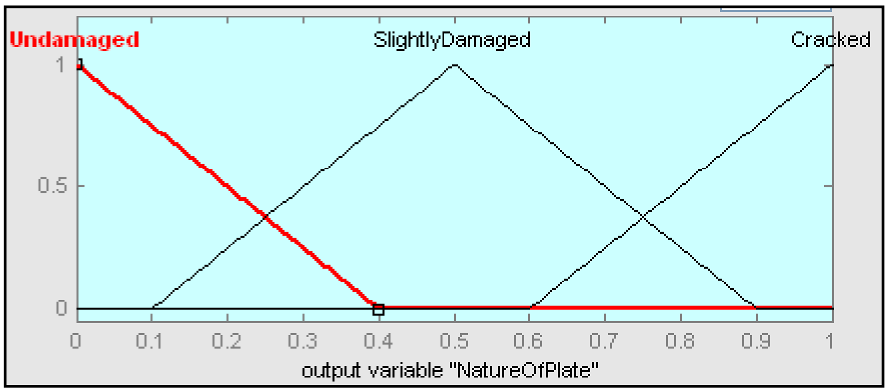


Fig. 5 Triangular-shaped membership function for consequent *NatureOfPlate*

The rules are typically in the format of

- *If Frequency is 'Low' and Average RMS is 'low' Then NatureOfPlate is* ' Damaged Plate' or
- *If Frequency is 'Low' or Average RMS is 'Low' Then NatureOfPlate is* ' Damaged Plate',

where the If part is called the 'antecedent' and the *Then* part is called the 'consequent'. The antecedents identified in the crack detection system are input factors. The antecedents and consequents are connected with help of 'and' or 'or' operators with use of negation operator if needed. After identifying the antecedents their labels with the range are identified, which depends on the common sense and the experience.

Table 2: Rule Base for the Crack Detection Fuzzy Inference System

Rule Number	**Frequency**	**Average Root Mean Square RMS**	**Standard Deviation**	**Result: Nature of Plate**
1	High	High	High	Undamaged plate
2	High	High	Low	Slightly Damaged
3	Medium	Medium	Medium	Slightly Damaged
4	Medium	Low	Low	Damaged Plate
5	Low	Medium	High	Slightly Damaged
6	Low	Low	Low	Damaged Plate

Fig. 5 shows the triangular membership function for the consequent NatureOfPlate/ *DegreeOfCrack*. Thus Y-axis shows the *DegreeOfCrack* value. This function is selected by trial and error method after trying other membership functions like Gaussian, Trapezoidal, Gaussian bell and others. It was observed that triangular function works well with the Crack Detection Fuzzy Inference System.

The relationship between the antecedents and consequents is expressed with help of the generated rule base. Table 2 shows a part of the rule base developed on basis of the experimental results found in [1]. If any of the input parameter labels like *Low, Medium or High* are *'true'* for a certain rule then that rule is said to be activated. About dozen rules are formulated. Some of the example rules are:

1. If (Frequency is High)and(AverageRMS is High)and(StdDeviation is High) then (NatureOfPlate is Undamaged)
2. If (Frequency is Medium)and(AverageRMS is Medium)and(StdDeviation is Medium) then (NatureOfPlate is Slightly damaged)
3. If (Frequency is Low)and (AverageRMS is Low) and (StdDeviation is Low) then (NatureOfPlate is damaged)
4. If (Frequency is Low)and (AverageRMS is Medium) and (StdDeviation is Medium) then (NatureOfPlate is Slightly damaged)

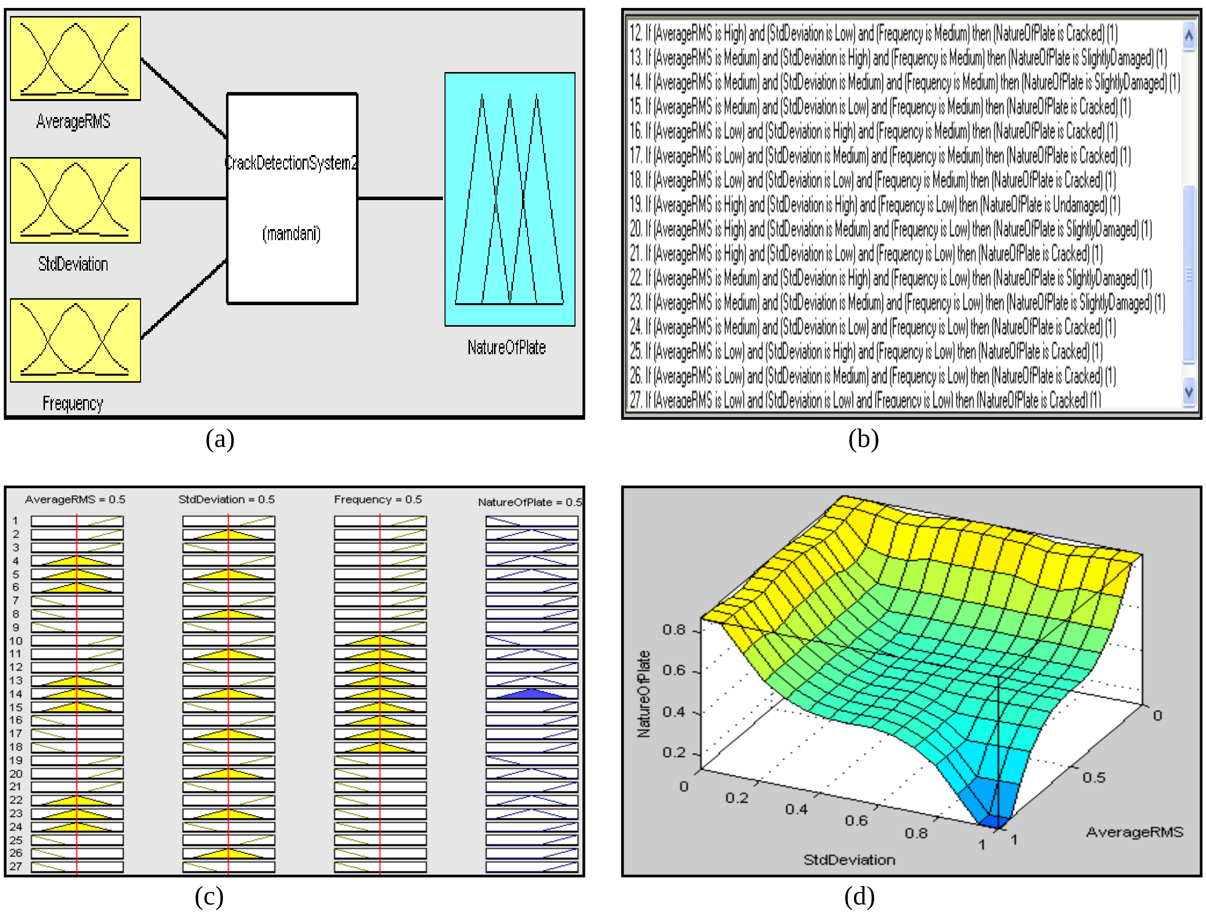


Fig. 6 Crack Detection Fuzzy Inference System (a) The FIS- Fuzzy Inference System, (b) The FIS rules, (c) The FIS Rule viewer, (d) The FIS surface viewer

Fig. 6 shows the software implementation for the Crack Detection Fuzzy Inference System. Fig. 6(a) shows the structure of the TISO (Triple Input Single Output) Fuzzy Inference System using Mamdani method [11]. This clearly expresses the structure of the system with three input parameters identified as input factors associated with some membership functions. This also shows presence of a single output – *NatureOfPlate*. Fig. 6(b) shows the

snapshot of Fuzzy Inference System Rule Editor Window. The rule base is added and updated with help of Rule Editor Window. Fig. 6(c) shows Fuzzy Inference System Rule Viewer, which shows fuzzy inference rule diagram. It shows the effect of each individual membership function of input factors affecting on the result. This gives a facility to change the values of the input parameters by moving the bar present on first three columns for the input factors which in turn updates the result found in fourth column. This window shows a result *NatureOfPlate* =0.5 (Slightly damaged), for inputs Average RMS = 0.5(medium), Standard deviation =0.5(medium), Frequency =0.5(medium).It is also seen that Rule number 14 was activated to generate the result. The Fig. 6(d) shows the surface viewer which displays the interdependence between the two inputs (Standard deviation, Average RMS) and the output result (Nature of Plate) in 3-dimensions.

The Proposed algorithm for Development of Crack Detection Fuzzy Inference System consists of following steps:

1. Identify the input and the output parameters for the Fuzzy Inference System.
2. Set the range for the input and output parameters. Their range is tabulated in Table 2 range.
3. Fuzzify the input parameters maps and observed non-fuzzy input space into suitable linguistic values.
4. Define membership function for each parameter. The membership function is triangular, Gaussian, trapezoidal etc.
5. Develop Fuzzy rule base.
6. The result is obtained by aggregating the result of each rule in the fuzzy rule base for the considered input.
7. Defuzzify the output and map it to nonfuzzy linguistic output value 'Degree of Crack'.

V. FPGA IMPLEMENTATION OF CRACK DETECTION SYSYEM

The Field-programmable gate array (FPGA) plays a significant role in rapid prototyping of a chip. It can be programmed and reprogrammed using reasonably priced hardware and software on the field. Here the hardware is the FPGA board and software is circuit design, implementation, debugging, verification and simulation software that sometimes are provided with the hardware. FPGA also is a cheaper option over the respective chip, taking into consideration the manufacturing cost and complexity of the chip. The FPGA is a general-purpose, multi-level Programmable Logic Device (PLD).

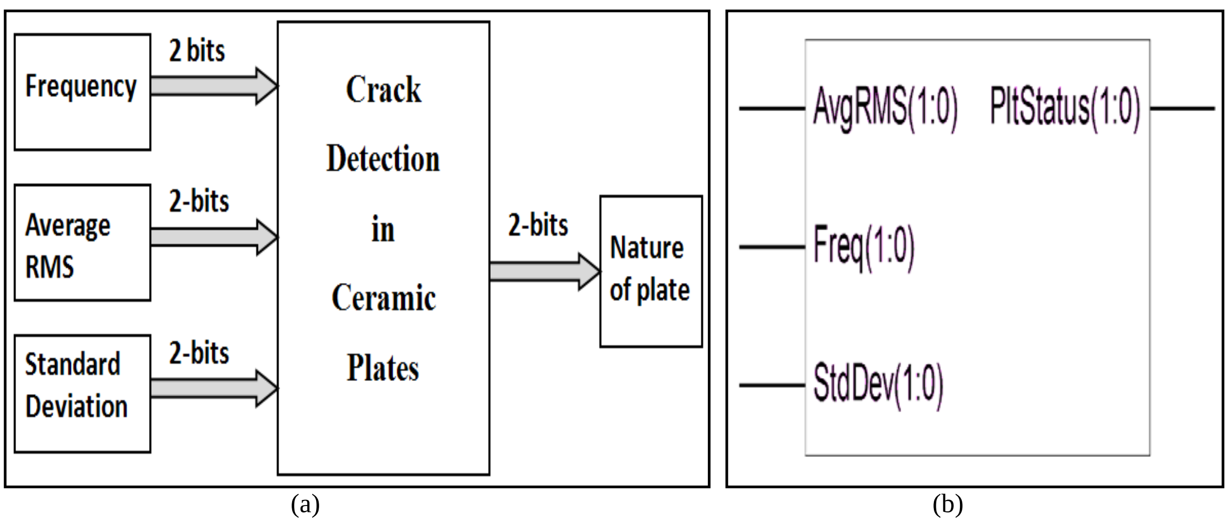


Fig. 7 FPGA implementation of Crack Detection (a). System design structure (b). RTL schematic

The reference [1] discusses design of a standalone device which can detect cracks and identify the source of impact. This motivates an attempt to develop a chip which can detect crack on basis of logic used in the Crack Detection Fuzzy Inference System discussed in Section IV. A rapid prototyping of the chip design is handled by FPGA

implementation of the crack design Fuzzy Inference System. To program or design FPGA a HDL is used. The steps for FPGA implementation [7] of the crack detection system are represented in a flowchart as shown in fig. 10(a). These steps are described below.

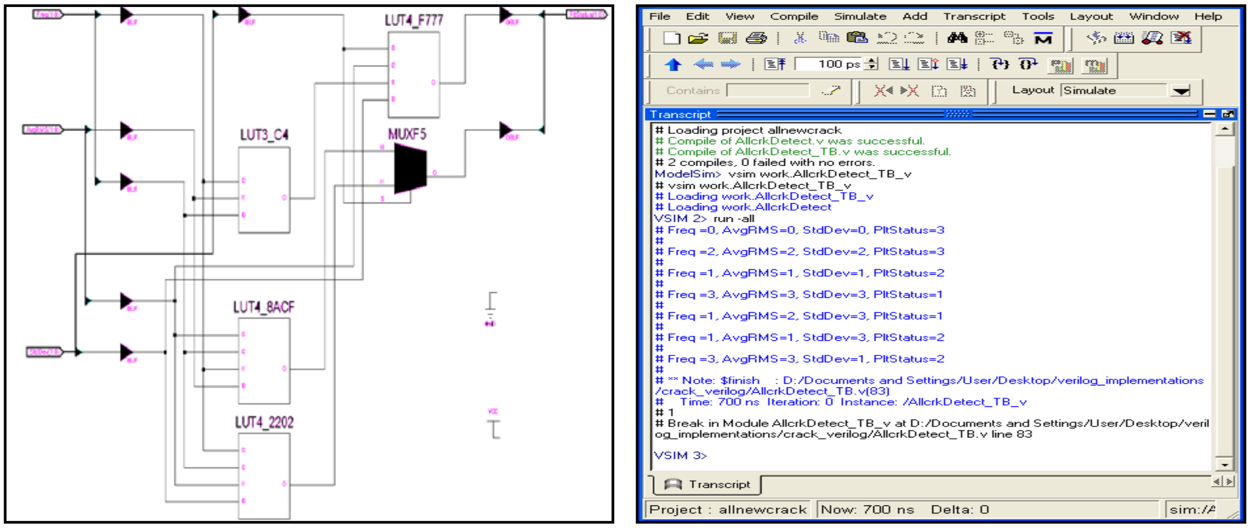
1. Identify the inputs and outputs for the Crack Detection chip. Determine the dimension of the system structure as seen in Fig. 7(a).
2. Develop HDL code for Crack Detection in ceramic plates.
3. Select device as FPGA and assign package pins for Crack Detection design on FPGA.
4. Generate a netlist PROM file to be downloaded on the FPGA.
5. Configure the FPGA and program FPGA; verify the design using input output signal pins/buttons on FPGA board.
6. Write a Test-bench file to simulate and verify the FPGA implementation.
7. Run the test bench file with help of any VLSI circuit debugging and simulation software.

Some of the advantages of the FPGA [10] implementation are rapid prototyping of the system, flexibility to change the rule-base or antecedents or consequent, and without much cost can be downloaded back on the FPGA. Different VLSI circuit design, implementation, verification and simulation software [8, 9, and 12] are used to design and implement fuzzy crack detection on the FPGA using HDL code. The Table 3 shows the consequent which is 2-bit bus representing the *Nature of Plate* codes and its interpretation. Table 3 shows the value of this output bus and the meaning behind the result. For example, if the result generated is '10', then it would mean that the plate is *slightly damaged*. The system design is expressed as a block diagram in Fig. 7(a). The antecedents are *Frequency*, *Average RMS*, *Standard Deviation* each 2-bit buses with '00', '01', '10' representing labels *Low*, *Medium* and *High* respectively.

Table 3: Crack Detection FPGA Implementation Output: Plate Status codes

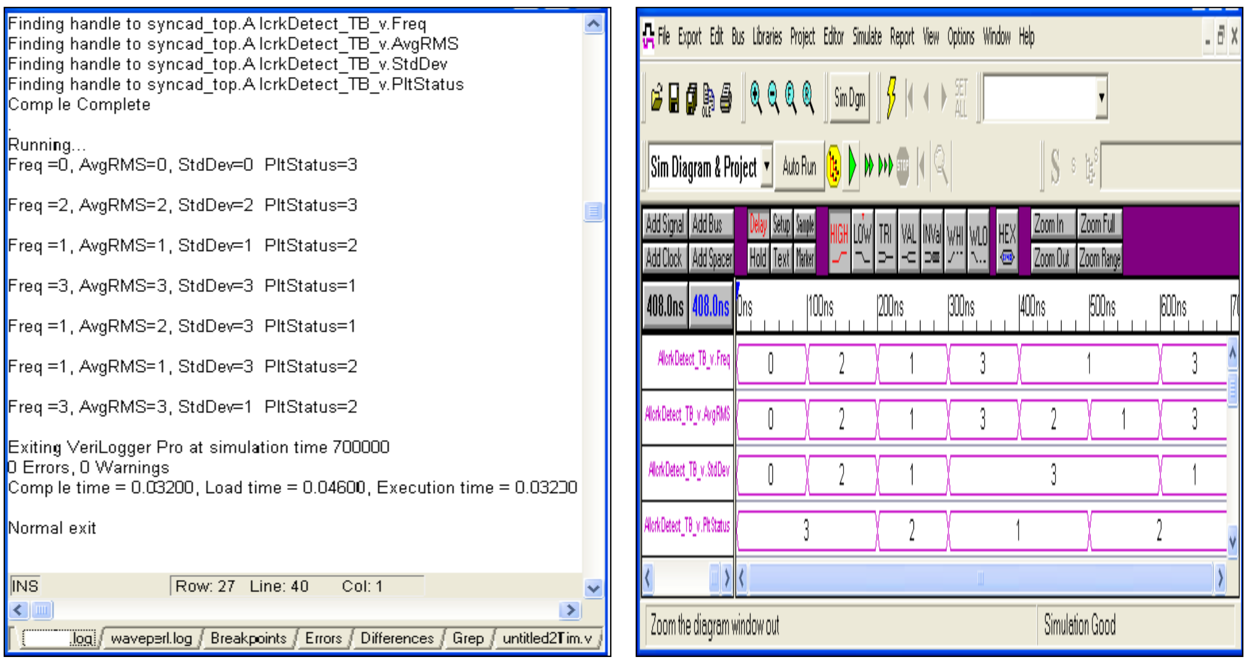
Nature of Plate Status	**Output 2-bit Code**	**Numerical Value**
Unknown	00	0
undamaged	01	1
slightly damaged	10	2
damaged	11	3

Fig. 7(b) shows the Register Transfer Level (RTL) schematic of the system developed. RTL schematic basically tells how the HDL code is interpreted by the synthesis tool and mapped with the target technology. RTL schematic view represents design in terms of macro blocks which further shows the detailed circuit with combinatorial logic mapped onto elementary logic function gates. Fig.8 (a) shows technology schematic and Fig 8(b) shows the result transcript of the software simulation [12] of the system developed. Technology schematic represents the design in terms of logic elements optimized to the target device. Fig 10(b) shows the Detailed RTL schematic for the design. The design and implementation of the crack detection system was also done using another VLSI circuit debugging and simulation software [9] which can be seen in Fig. 9(a) and Fig. 9(b). Table 4 shows the analysis of device usage for the crack detection implementation. Here LUT stands for Lookup table. Slice is an elementary programmable logic block which includes: two 4-input LUTs, two multiplexers, arithmetic logic unit, and two 1-bit registers. It is seen that the results obtained using Fuzzy Inference System (FIS) developed using Fuzzy Logic software matches reasonably good with the results obtained on the FPGA board.



(a) (b)

Fig. 8 Crack Detection (a) Technology Schematic, (b) Transcript Simulation

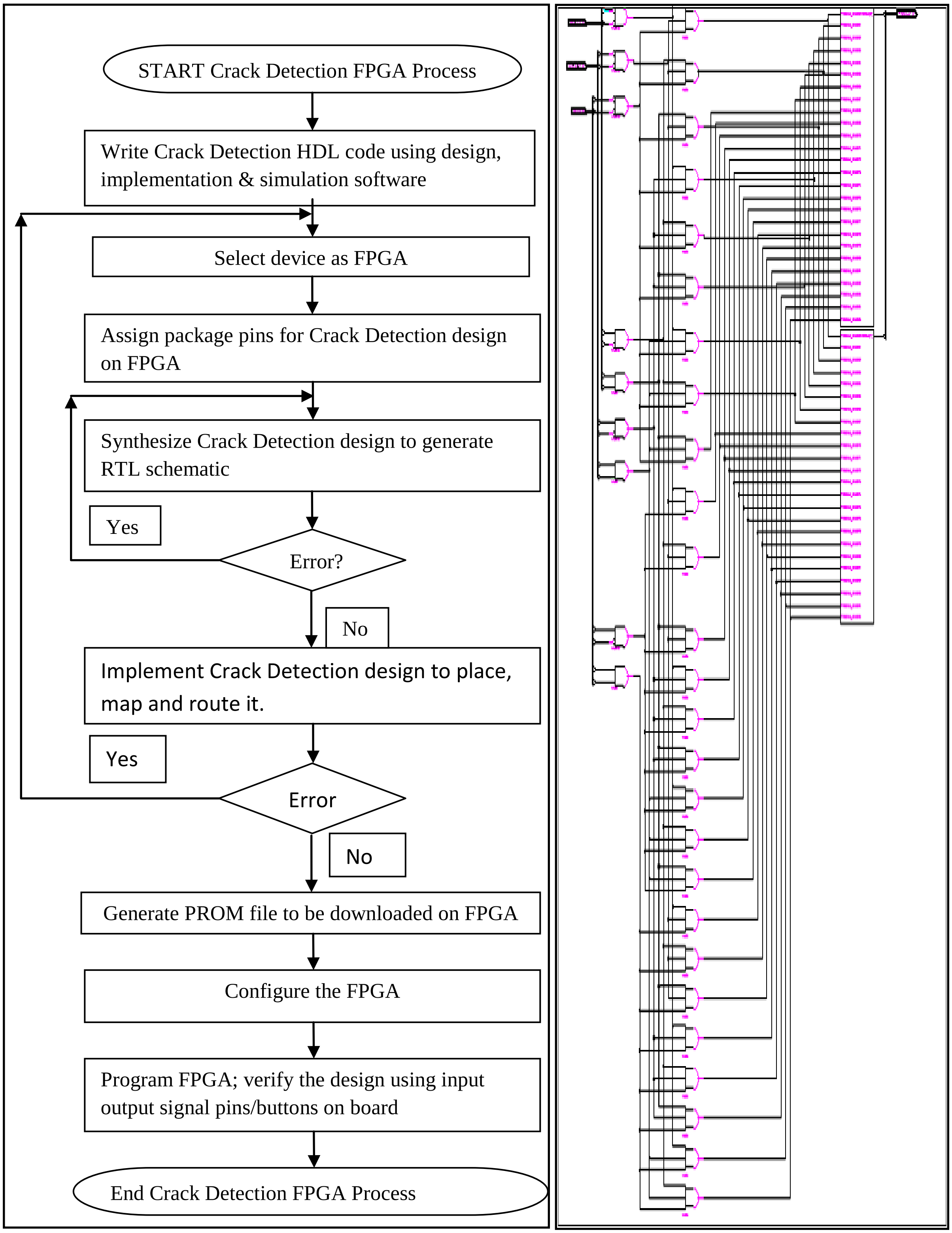


(a) (b)

Fig. 9 Crack Detection Simulation (a) HDL Log, (b) Waveform Simulation

Table 4: Analysis of FPGA Implementation of Crack Detection

Metric	**Used**	**Available**	**Utilization**
Number of 4 input LUTs	4	3,840	1%
Number of Slices occupied	2	1,920	1%
Additional JTAG gate count for IOBs	384	-	-
Number of bonded IOBs:	8	173	4%
Total equivalent gate count for design	27	-	-



(a) (b)

Fig.10 Crack Detection a. FPGA Implementation process flowchart, b. Detailed RTL Schematic

This paper describes an integrated approach towards crack detection, which includes both Fuzzy Inference System and the FPGA implementation. Fig. 11 describes this integrated approach. The test circuit [1] captures vibrations through the plate and generates waveforms which can be displayed on an oscilloscope. The test circuit results in the form of waveforms are further decoded to obtain the data which acts as input for the crack detection Fuzzy Inference System. This FIS generates the result '*Nature of Plate*' Є {Unknown, Undamaged, Slightly damaged, Damaged}. The rule base from Fuzzy Inference System is implemented using FPGA. Thus it behaves similar to the Fuzzy Inference System. The test circuit results in the form of waveforms are further decoded to obtain the data in term of bits which acts as input for the crack detection FPGA Implementation. The FPGA implementation results in a conclusion about the status of the '*Nature of Plate*' Є {Unknown, Undamaged, Slightly damaged, Damaged}.

The Proposed algorithm for an Integrated Approach towards Crack Detection consists of following steps:

1. Extract the parameters from the data obtained by the test circuit as shown in Fig. 2.
2. Identify the input parameters which are instrumental in deciding the nature of plate. The parameters selected for Crack detection are : { *Frequency*, *Average RMS*, *Standard Deviation* }
3. Set the range for the input and output parameters.
4. Fuzzify the input parameters maps an observed non-fuzzy input space into suitable linguistic values
5. Define membership function for each parameter. It is triangular, Gaussian, trapezoidal etc.
6. Develop Fuzzy rule base.
7. The result is obtained by aggregating the result of each rule in the fuzzy rule base for the considered input.
8. Defuzzify the output and map it to nonfuzzy linguistic output value 'Degree of Crack'.
9. Identify the inputs and outputs for the Crack Detection chip. These parameters are same as we diagnosed for the Fuzzy Inference System. Determine the dimension of the system structure as seen in Fig. 7(a).
10. Develop HDL code for Crack Detection in ceramic plates.
11. Select device as FPGA and assign package pins for Crack Detection design on FPGA.
12. Generate a netlist PROM file to be downloaded on the FPGA.
13. Configure the FPGA and program FPGA; verify the design using input output signal pins/buttons on FPGA board.
14. Write a Test-bench file to simulate and verify the FPGA implementation.
15. Run the test bench file with help of any VLSI circuit debugging and simulation software.

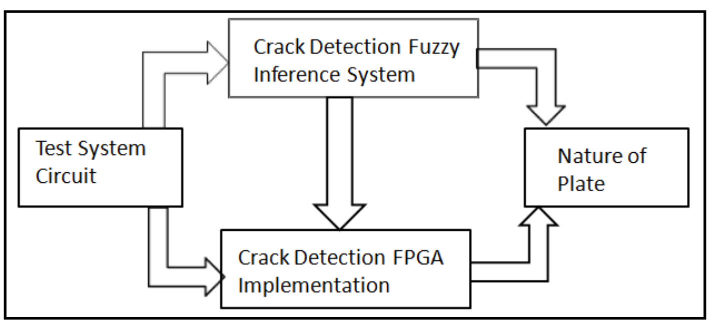


Fig. 11 An integrated approach towards Crack Detection.

VI. CONCLUSION

The Fuzzy Logic modeling approach is explored and presented as a candidate for the detection of cracks in armor plates using soft computing methods. The Crack Detection Fuzzy Inference System is developed with help of Fuzzy Logic Software to model the relationship between the {Frequency, Average Root Mean Square RMS voltage, Standard Deviation} and the Degree of crack. This Fuzzy Logic approach overcomes the human error present in

manual method of comparing the waveforms with that of an undamaged plate. The Crack Detection Fuzzy Inference System generates acceptable results and needs very little effort as compared to a conventional mathematical method. Further an attempt is made to incorporate the Crack Detection Fuzzy Inference System on a chip, which can be part of a handheld device. The rule-base is incorporated in the chip with help of a Hardware Description Language. The VLSI -Very Large Scale Integration design is done with the help of the Field-programmable gate array (FPGA) implementation. FPGA is Hardware prototype for the chip.

We suggest a soft computing approach for the detection of cracks. We have proposed a procedure by which VLSI chips can be developed to detect crack in armor plates. We have suggested FPGA implementation of the proposed method. The method suggested previously [1] detects the crack by manual comparison of waveforms obtained. The procedure suggested here is potentially superior to the existing methods as the procedure is automated and is implemented on a chip. We have utilized Fuzzy Logic rules for detection of cracks. The rule base developed has been written as HDL code. The implementation of the HDL code is done in the form of a circuit. The procedure can be easily implemented to automatically detect the crack in armor plates. It is hoped that this proposed technique will be useful for the research workers in the area of crack detection. The suggested software and hardware prototype to automate the crack detection process here will lead to more reliable, robust and automated techniques for the detection of crack. The proposed models can be extended to include more parameters and factors. The development of a chip will play a critical role in real time crack detection applications.

Disclaimer: Reference herein to any specific commercial company product process or service by trade name, trademark, manufacturer, or otherwise, does not necessarily , constitute or imply its endorsement, recommendation, or favoring by the United States Government or the Department of the Army (DoA). The opinions of the authors expressed herein do not necessarily state or reflect those of the United States Government or the DoA and shall not be used for advertising product endorsement purposes.

VII. REFERENCES

[1]. Thomas J. Meitzler, Gregory Smith, Michelle Charbeneau, Euijung Sohn, Mary Bienkowski, Ivan Wong and Allen H. Meitzler, , “Crack Detection in Armor Plates Using Ultrasonic Techniques”, Materials Evaluation, pp. 555-559, June, 2008.

[2]. Harpreet Singh, Shashank Kamthan, Arati M. Dixit, Adam Mustapha, Thomas Meitzler, Allen Meitzler, Fuzzy and NeuroFuzzy Approach for Crack detection in Armor Plates, SERP'08, Las Vegas, July 2008

[3]. John Yen, Reza Langari, “Fuzzy Logic: Intelligence, control and information” Prentice Hall. First edition, 1998.

[4]. Harish Ch. Das, Dayal R. Parhi “Online fuzzy logic crack detection of a cantilever beam”. International Journal of Knowledge-based and Intelligent Engineering Systems, Dec. 2008, p157-171.

[5]. Zadeh Lotfi A, “Fuzzy sets”, Inf. Control 8, 338-353, 1965.

[6]. Shashank Kamthan, Harpreet Singh, Arati M. Dixit, Vijay Sharma, Thomas Reynolds, Ivan Wong, Thomas Meitzler, Fuzzy Logic Approach for Impact Source Identification in Ceramic Plates", The 2009 International Conference on Artificial Intelligence (ICAI'09), July 2009

[7]. Arati M. Dixit, Harpreet Singh**,** "FPGA Implementation of Fuzzy Reliability of Unmanned Vehicles", The 2009 International Conference on Artificial Intelligence (ICAI'09), July 2009

[8]. Xilinx Inc.: The Programmable Logic Data Book (2000)

[9]. SynaptiCAD Inc: BugHunter Pro and VeriLogger simulators, version 12, December 2007

[10]. Stephen Brown, Jonathan Rose, "FPGA and CPLD Architectures: A Tutorial," IEEE Design and Test of Computers, vol. 13, no. 2, pp. 42-57, June 1996.

[11]. The MathWorks Inc : Fuzzy Logic Toolbox™ 2 User’s Guide, September 2009

[12]. Model Technology Incorporated : Start Here for ModelSim® SE , August 2002

[13]. http://www.asnt.org/publications/materialseval/basics/apr98basics/apr98basics.htm

[14]. Zadeh, Lotfi A., "Fuzzy Logic, Neural Networks, and Soft Computing," Communications of the ACM, March 1994, Vol. 37 No. 3, pages 77-84.

[15]. Peng Zheng, David W. Greve, and Irving J. Oppenheim, “Crack Detection with Wireless Inductive-Coupled Transducers,” Proc. SPIE, Vol. 6932, 69321H (2008); doi:10.1117/12.775917

[16]. Yves Berthelot, Jianmin Qu and Lourence Jacobs, “Crack Detection by Ultrasonic Guided Waves”.

[17]. J. H. Tong and T. T. Wu, “A Portable Transient Elastic Wave System for In-situ Nondestructive Evaluation of Concrete,” NDT.net – June 2001, Vol 6 No. 6.